Morphometric and taphonomic analysis of granular ark (*Anadara granosa*) dominated shell deposits of Blue Mud Bay, northern Australia

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ABSTRACT

Metrical analyses of complete mollusc shells have commonly been used to examine aspects of prehistoric mollusc demography, and by extension to investigate potential human exploitation of a variety of species. Recently it has been highlighted that several taphonomic processes, such as fragmentation, have the potential to introduce size bias into these archaeological samples, particularly towards smaller size classes, and thus the potential to significantly skew results of these metrical analyses. This is investigated here by deriving morphometric equations for the sand/mudflat bivalve *Anadara granosa*, a species prevalent in archaeological sites across northern Australia. A linear regression model based on a series of valve measurements, resulting in high coefficients of determination, demonstrates strong predictive power for size reconstruction. The effects of fragmentation on assemblages from two case study sites are then examined as a means of reviewing issues of differential size preservation, variation in mean valve size, and evaluating the strength of previous interpretations of intensive human exploitation in Blue Mud Bay. Based on these analyses it appears that *A. granosa* mean size is not significantly affected by fragmentation as other species described in the literature, and previous interpretations retain their validity.

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1. Introduction

Archaeological investigations into the potential effects of human exploitation on molluscan species have relied heavily on the analysis of metrical data, and in particular the investigation of mean size reductions and shifts in the size-age structure as a measure of potential resource depletion (e.g. Antczak et al., 2008; Baez and Jackson, 2008; Bailey et al., 2008; Bailey and Craighead, 2003; Bailey and Milner, 2008; Bourke, 2000, 2002; Braje et al., 2007; Erlandson et al., 2008; Faulkner, 2009; Jerardino, 1997; Jerardino et al., 2008; Lightfoot and Cerrato, 1988; Mannino and Thomas, 2001, 2002; Masse et al., 2006; Milner et al., 2007; Morrison and Cochrane, 2008; Nielsen, 2008; Parkington, 2008; Peacock, 2000; Peacock and Mistak, 2008; Rick et al., 2008; Spennemann, 1987; Swadling, 1976, 1977). In many of these cases, and regardless of whether the focus has been on gastropod or bivalve species, there has been a reliance on measurements of complete shells. Recent studies have indicated that this approach can be problematic due to the often small samples and fragmentary nature of mollusc remains (both marine and freshwater) in the archaeological record, a pattern that has the potential to significantly skew the results of

metrical analyses due to differential size preservation. Where analyses of shell size are based entirely on complete or whole specimens there is a degree of uncertainty as to whether the observable patterns are biased in favour of either the larger or smaller size classes as a result of taphonomic processes, and would therefore not accurately reflect shell size within the assemblage (Jerardino and Navarro, 2008: p. 1024).

Related to this issue, a large number of studies conducted worldwide have employed morphometric techniques, whereby shell length is estimated from fragmented remains based on morphometric equations derived from the measurement of recognisable or readily preserved shell features (see for example Andrews et al., 1985; Buchanan, 1985; Cabral and da Silva, 2003; Ford, 1989; Gardner and Thompson, 1999; Hall, 1980; Jerardino and Navarro, 2008; Jerardino et al., 1992; Marelli and Arnold, 2001; Peacock and Mistak, 2008; Peacock and Seltzer, 2008; Randklev et al., 2009; Ulm, 2006; Whitaker, 2008; Yamazaki and Oda, 2009). In addition to the use of morphometric equations, a third method for estimating original shell size is the use of a bivalve hinge width and angle template to reconstruct size within 1 cm increments from hinge fragments. This method has been successfully applied in analyses of California mussel (*Mytilus californianus*) recovered from sites along the California coast (e.g. Braje et al., 2007: p. 745; Jones and Richman, 1995; Whitaker, 2008: p. 1118). In many respects the same principles apply for this method

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as for the use of morphometric equations, as it has been demonstrated that hinge width and angle are strongly correlated with overall shell length for this taxon (Jones and Richman, 1995; Whitaker, 2008: p. 1118). This growing body of research has demonstrated the utility of morphometric methods to increase sample size and to overcome these potential problems in size/age analyses of molluscan assemblages.

The recent work of Jerardino and Navarro (2008) is particularly pertinent in this context. This study focused on the investigation of two dominant limpet species (*Cymbula granatina* and *Scutellastra granularis*) found within midden deposits along the West Coast of South Africa, demonstrating that sample sizes of shell measurements increase with the use of fragmentary material, as well as highlighting potential preservation biases within these assemblages (Jerardino and Navarro 2008: pp. 1024, 1026–1027). The particular taphonomic processes operating on these South African midden deposits during and after their formation biased the preservation of both *C. granatina* and *S. granularis*, with increased levels of preservation of the smaller shells. The significance of this work, however, goes beyond a species or site-specific context, providing broader relevance to investigations of shell deposits and taphonomy. Jerardino and Navarro (2008: p. 1027) note that different combinations of taphonomic processes (in particular species mineralogy and robusticity, variations in rates of accumulation and the extent of trampling, acidity and burning) may result in quite different patterns of differential preservation, including an opposite trend in preservational bias to those reported from the South African case study. These findings raise the possibility of differential preservation bias in shell deposits generally, and therefore the suggestion that these analyses and comparisons be made across a range of depositional contexts and research programs (both new and existing) (Jerardino and Navarro 2008: p. 1027) require serious consideration.

As such, there are a number of implications stemming from this prior research for more recent interpretations of the *Anadara granosa* dominated shell mounds of northern Australia. While there has been considerable debate surrounding the role of these sites in mid to late Holocene coastal economies across the northern tropical coast of Australia (Bailey, 1975, 1993; Bourke, 2000, 2002; Hiscock, 1997, 1999, 2008; Morrison, 2003), recent research has suggested that these sites represent intensive exploitation of this sand and mudflat species to a degree not seen prior to, or since, the main period of mound formation (falling approximately 3000–500 years BP) (Faulkner, 2006, 2009). As these interpretations are based only on the analysis of complete *A. granosa* valves to determine variation in the size/age structure of the assemblages through time, the suggestion of fragmentation and size bias warrants further testing. The aim here is to evaluate this notion via the development of morphometric equations for *A. granosa*, building in particular on the recent work of Jerardino and Navarro (2008) noted above, and to apply these methods to case study sites from northern Australia. These sites present very different morphological characteristics (midden vs. mound), chronological patterns (slow vs. rapid formation) and fragmentation rates as a basis for evaluating the complexity of potential bias in these shell assemblages.

2. Control sample structure and regression models

The modern reference collection of 96 *A. granosa* valves held at the Queensland Museum, Brisbane, forms the control sample used in this study. The documentation available for this sample indicates that the majority of the specimens were collected live, or were purchased shortly after death. This sample does not represent collection from a single location, but instead represents the recorded geographic distribution of this species (Fig. 1). *A. granosa* are
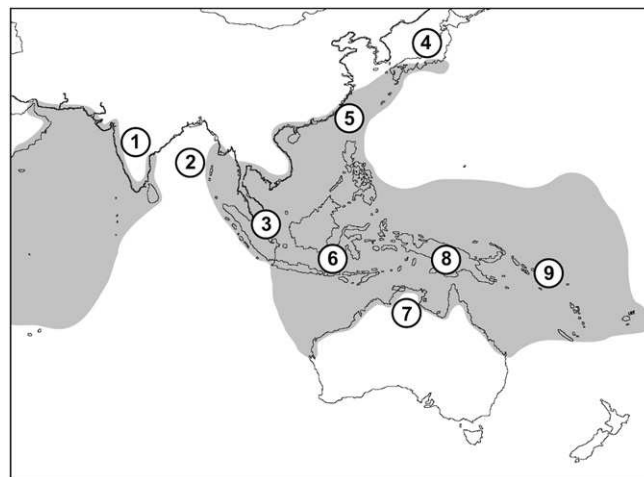

Fig. 1. Modern geographic distribution of *Anadara granosa* across the Indo-West Pacific region (numbers refer to broad origin location of samples held by the Queensland Museum: 1, India; 2, Bay of Bengal; 3, Malaysia; 4, Japan; 5, Taiwan; 6, Indonesia; 7, Northern Australia; 8, Papua New Guinea; 9, Solomon Islands).

widespread across the Indo-West Pacific, from East Africa to Polynesia; north to Japan and south to the north Australian coastline (Lamprell and Healy, 1998: p. 54; Poutiers, 1998: p. 147). Favouring the soft substrates of large estuarine mudflats, the optimal habitats for *A. granosa* are within the intertidal and marginally subtidal zone of shallow inlets or bays, bordered on the landward margin by mangrove forests (Broom, 1985: pp. 4–7; Pathansali and Soong, 1958: p. 27; Tiensongrusmee and Pontjoprawiro, 1988). The geographic spread of the control sample noted above is quite important, with individuals in the sample representing a diverse range of environmental and climatic conditions, particularly as *A. granosa* has either disappeared entirely from natural coastal habitats since approximately 500 years ago, or now only exists in very low densities along the north Australian coastline.

The measurements selected for analysis of *A. granosa* are presented in Fig. 2. General valve morphology is an important consideration, as *A. granosa* is characterised as being robust, with a relatively straight taxodont hinge (strong and oblique at the posterior and anterior ends), wide to concave cardinal area, and strongly protruding umbones (Lamprell and Healy, 1998: pp. 44, 52–54; Poutiers, 1998: p. 142). Common valve measurements included here are valve length, valve height and hinge length (after Claassen, 1998: p. 109, Fig. 20). Other measurements were selected based on prior knowledge of breakage patterns for this species in both shell midden and mound sites (i.e. which parts of the valve were most likely to survive). In addition, due to the robusticity of the umbo and its prevalence in archaeological assemblages, measurements of umbo length and height were also included. Other measurements, such as those based on valve length: weight ratios (e.g. Bourke, 2000: p. 70, 2002: p. 38) and those that rely on clear identification of the pallial line and/or the anterior or posterior adductor scars, are difficult to take due to differential patterns of weathering and dissolution, discolouration and marginal fragmentation (see for example Peacock, 2000; Peacock and Mistak, 2008; Peacock and Seltzer, 2008; Randklev et al., 2009).

Table 1 shows the number of control sample valves analysed, the size ranges and descriptive statistics for each of the valve part measurements. As *A. granosa* are equivalve the sample was not separated into left or right valves, thus, aggregated data are used in this analysis (e.g. Randklev et al., 2009: p. 208). All measurements were obtained using Mitutoyo CD-8″CX digital calipers to the nearest 0.01 mm, and the regression models were constructed
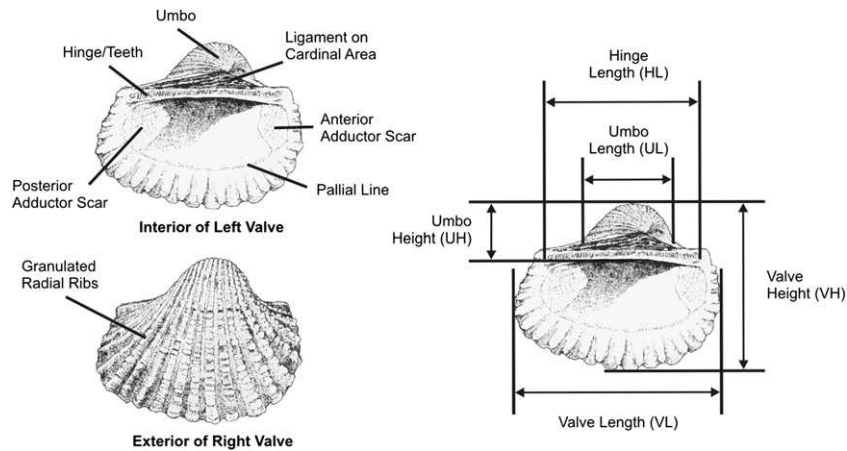
Fig. 2. *A. granosa* valve terminology and measured attributes for establishing the morphometric equations (VL, valve length; VH, valve height; HL, hinge length; UL, umbo length; UH, umbo height) (valve redrawn from Poutiers, 1998: 147).

using SPSS version 17.0. As with previous studies (e.g. Jerardino and Navarro, 2008: p. 1025), it was found that a linear regression model ($y = a + bx$) fitted the data best (Fig. 3). The parameters (a and b) and coefficient of determination (r^2) are also presented in Table 1 for each valve part measurement. The high coefficient of determination values (≥ 85) indicates the strong and accurate predictive value of each measurement. To demonstrate the utility of the methods outlined here, particularly in determining potential bias in the investigation of *A. granosa* size/age structure in archaeological assemblages, the full range of measurements are applied to excavated samples obtained from *A. granosa* dominated shell midden and mound sites located in northern Australia.

3. Northeast Arnhem Land (Australia) shell midden and mound sites

The study area is the Point Blane peninsula, located within the coastal plains of Blue Mud Bay in northeast Arnhem Land (Fig. 4A). The Point Blane peninsula is the central of three peninsulas on the northern coastal margin of Blue Mud Bay. Of the 141 archaeological sites recorded within this area, 38 horizontally-spread shell middens are situated on the present day coastline within Myaoola Bay, and 82 shell midden and shell mound sites, all dominated by *A. granosa*, are located on the edges of the Dhuruputjpi freshwater wetland (an infilled former embayment) that feeds into Grindall Bay. The sites that form the case study for this investigation are the shell midden BMB/067b in the small bay to the north of Point Blane on the southern tip of the peninsula, and the shell mound BMB/071 located on the margin of Grindall Bay (Fig. 4B and C). Although both are dominated by *A. granosa*, these two sites present very different morphological characteristics and depositional histories.

BMB/067b is a dispersed midden located on the edge of the low-lying swamp, measuring roughly 400 m by 30 m, with some

Table 1
Numbers of *Anadara granosa* valves analysed from the control sample, including size ranges and the parameters of morphometric equations for the estimation of total valve shell length from measurements on valve elements.

Measurement (x variable)	n	Min	Max	Mean	s.d.	a	b	r^2
Valve Length	96	10.11	69.05	38.46	11.94			
Valve Height	96	8.32	56.03	30.97	10.00	1.85	1.18	0.98
Hinge Length	78	6.34	47.74	23.79	8.75	3.59	1.47	0.98
Umbo Length	94	3.40	27.84	14.06	4.55	4.15	2.44	0.85
Umbo Height	78	1.93	14.14	6.92	2.83	8.18	4.39	0.91

Linear regression equation ($y = a + bx$); In all cases $p < 0.001$.

discrete and concentrated shell patches across the general low-level surface scatter of shell. The 1 m^2 test-pit, excavated in eight excavation units or levels of approximately 5 cm, reached a depth of 35 to 40 cm. The deposit contained a large amount of shell material (10,624.0 g) and lateritic/rock deposits (5859.1 g) in a loose, dark humic matrix. Charcoal (2.3 g), fish bone (46.1 g), fragments of crab carapace (2.0 g) and four stone artefacts (64.4 g) formed the minor constituents of the excavated material. As well as *A. granosa*, Venus shell/clams (*Marcia hiantina* and *Gafrarium* ssp.) and the Box mussel (*Septifer bilocularis*) form the sub-dominant molluscan taxa within this site. All conventional radiocarbon ages were converted to calendar years using the CALIB (v5.0.1) calibration program (Stuiver and Reimer, 1993) with the marine 04.14c calibration curve dataset (Hughen et al., 2004) and the northeast Australian ΔR correction value of 12 ± 7 (Reimer and Reimer, 2008). Radiocarbon dates on shell obtained from the upper and lower excavation units of BMB/067b (Table 2) indicate a long sequence of deposition, beginning at approximately 1500 cal BP and terminating at approximately 600 cal BP (Faulkner, 2006, 2008: p. 83). All eight of the units excavated were investigated, and analysis of size based entirely on measuring length of complete valves (Fig. 5A) indicates that there is no significant change in *A. granosa* size throughout the deposit (ANOVA $F = 0.834$, df $= 1029$, $p = 0.559$).

In contrast, BMB/071 is a relatively large mound, measuring 19.8 m by 19.4 m, with a height of 1 m, and is positioned fairly centrally within a large cluster of 25 shell midden and mound sites. The 1 m^2 test-pit, excavated in 11 excavation units or levels of approximately 5 cm, reached a depth of 50–60 cm. The deposit is characterised by densely packed *A. granosa*, with the Trough clam (*Mactra abbreviata*) as the sub-dominant species. The deposit revealed very little in the way of sedimentary matrix, with fine rootlets extending through the first 30 cm of the excavation. Molluscan remains dominate the deposit (28,373.2 g), with minor amounts of laterite and rock (123.8 g), charcoal (6.4 g), fish bone and otoliths (3.6 g), fragments of crab carapace (1.2 g) and two small stone artefacts (0.9 g). The base of deposit consisted of a matrix of yellow brown clay and laterite, with highly fragmented shell material. Previous investigations have highlighted the two-phase pattern of deposition within BMB/071 (Table 2), with one initial phase of occupation beginning approximately 1500 calBP followed by a second phase between approximately 1300 and 1200 cal BP (Faulkner, 2006, 2008: p. 83, 2009: pp. 825–826). Previously reported results following a detailed investigation of mean valve size within this site also indicates that there is a high
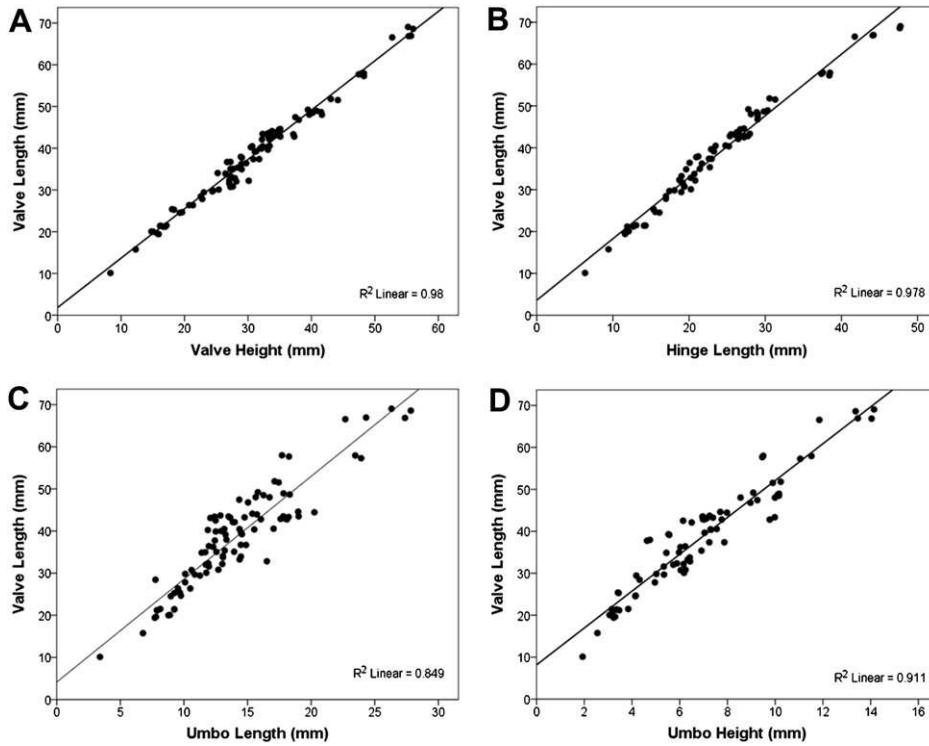
Fig. 3. Scatterplots of valve length vs. valve height (A), hinge length (B), umbo length (C) and umbo height (D) on modern *A. granosa* samples.

degree of variability and data dispersion through the deposit (ANOVA $F = 31.117$, $df = 3524$, $p = 0.000$; Spearman's $r_s = 0.771$, $r^2 = 0.636$, $p > 0.05$), with a significant size decrease between the lower and upper excavation units ($t = 8.253$, $df = 193$, $p < 0.001$) (Faulkner, 2009: p. 829). In addition to this general pattern, post-hoc comparisons using the Tukey HSD test indicates that mean valve size between excavation units three and five, and excavation units 9 and 11, are significantly different at 0.05 level (Fig. 5B).

4. Fragmentation

While potentially very time consuming to identify and count large quantities of broken shell, an analysis of shell fragmentation can provide important information regarding post-depositional processes affecting shell preservation and recovery (Mannino and Thomas, 2001; and discussion in Wolverton et al., 2009). The first step, therefore, is to investigate whether there is indeed a significant
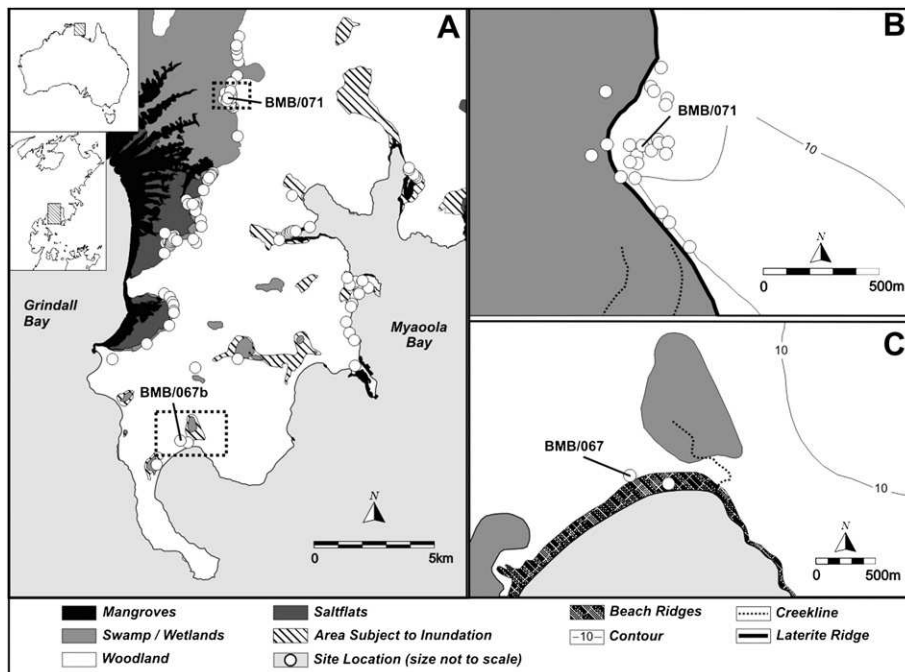

Fig. 4. The Point Blane Peninsula study area (A) and location of sites BMB/071 (B) and BMB/067b (C).

Table 2
Radiocarbon age estimates and 2σ calibrated age ranges obtained from sites BMB/067b and BMB/071.

Site Code	Depth (cm)	Lab Code	Sample	$\delta^{13}C$	^{14}C Age	2σ Calibrated Age BP
BMB/067b	0–2	Wk-17745	*A. granosa*	2.2 ± 0.2	1063 ± 35	675–543
	27–31	ANU-11714	*A. granosa*	2.0 ± 0.2	2010 ± 80	1762–1365
BMB/071	0–3	ANU-11722	*A. granosa*	2.9 ± 0.2	1700 ± 60	1361–1105
	19–24	ANU-11723	*A. granosa*	-2.5 ± 0.2	1810 ± 60	1495–1242
	42–46	ANU-11724	*A. granosa*	3.1 ± 0.2	1980 ± 60	1683–1375

Calibration data from CALIB 5.0.1, Marine04, $\Delta R = 12 \pm 7$ (Hughen et al., 2004).

relationship between fragmentation patterns and mean shell size within these assemblages. Relative abundance estimates (MNI and NISP), fragmentation ratios and mean *A. granosa* valve length by excavation unit per site are presented in Table 3. Fragmentation was here assessed by calculating the ratio of NISP to MNI throughout the assemblage (see Keegan et al., 2003; Morrison and Cochrane, 2008). The NISP:MNI ratio calculates the approximate number of fragments per individual based on relative abundance counts within individual excavation units, where a value of 1 indicates that all identified shells are whole and both NISP and MNI are therefore equal. Increasing values document higher degrees of fragmentation within these assemblages. It is important to note that the recovery or excavation methods used have the potential to influence fragmentation levels depending on the nature of the deposit itself. For example, recovery becomes more difficult and the chance of excavation-induced fragmentation will increase where shells within the deposit have been cemented in a hard, dried matrix of very fine sediment (such as fine clays) or calcium carbonate. This was not the case for either BMB/067b or BMB/071, even in the densely compacted shell deposit of the latter site, with relatively free or unhindered trowel excavation of the shell able to proceed, thereby minimising the effects of fragmentation via the excavation process. Therefore, variations in the degree of shell fragmentation throughout the sites in this study should correspond with phases of increased or decreased occupation. Based on experimental research, it has been suggested that variations in the degree of shell fragmentation may relate more to post-depositional processes rather than those activities occurring at the time of discard, reflecting the intensity of human activity at a site (Claassen, 1998: p. 58; Muckle, 1985: pp. 68, 75–78; Stein, 1992: pp. 148–149). For example, when the rate of site deposition is low, cultural material like stone artefacts, shell and bone are exposed on the surface for longer periods, and thus subjected to higher degrees of weathering and fragmentation. Conversely, when deposition is rapid, the length of exposure time and the degree of weathering and fragmentation is lessened (Bourke, 2000: p. 119; Hiscock, 1985: pp. 89–90; Jerardino and Yates, 1997: p. 46).

The pattern of shell fragmentation in BMB/067b shows that the level of fragmentation demonstrates a minor increase from a relatively lower level at the base of the site, peaking within the upper excavation units closer to the surface of the site (Fig. 6A). Overall the level of fragmentation within this site is quite low. Given the position of the site on the margins of a swamp and a comparatively lower rate of site formation and discard over the period of occupation, this may be more indicative of rapid deposition through natural sedimentation processes occurring during its formation and after abandonment of the site, therefore protecting the site to a certain degree from weathering and trampling. Although fragmentation levels are low in this midden, mean valve size by fragmentation ratio has been plotted in Fig. 6B to investigate whether there is a relationship between these variables. The relationship between mean valve size and fragmentation within this site is weak (Pearson's $r = 0.512$, $r^2 = 0.262$, $p = 0.195$), suggesting that fragmentation levels have not skewed *A. granosa* mean sizes as viewed through the original analysis of complete valves. In shell mound BMB/071, with the exception of the fragmentation ratio for *A. granosa* in excavation unit 11, the rate of fragmentation increases throughout the deposit (Fig. 6C). This pattern possibly relates to post-depositional processes of weathering, fragmentation and compaction since abandonment of the site approximately 1200 years ago. A period of increased exposure may also account for the anomalous pattern in fragmentation in excavation unit 11. The higher rate of fragmentation at the base of the site may indicate a hiatus in occupation during the first occupation phase following the initial period of shell discard in this location. In contrast with BMB/067b, the correlation coefficients indicate that there is a significant relationship between mean valve size and the level of fragmentation (Pearson's $r = -0.816$, $r^2 = 0.666$, $p = 0.048$) (Fig. 6D) despite the r^2 value of 0.666 indicating a degree of data dispersion.

These results demonstrate the differential effects of taphonomic processes on shell deposits, although it does appear that the relationship between fragmentation rates and size representation is variable, and not a simple one-to-one correlation. The importance of fragmentation in archaeological shell deposits, particularly in relation to investigations of potential human impact on mollusc populations in the past, is the connection between fragmentation and valve size. As noted above, it has recently been suggested by
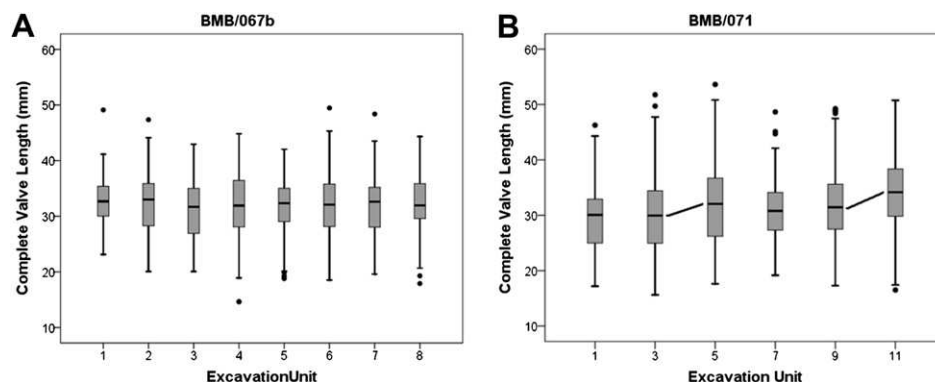

Fig. 5. Boxplots of *A. granosa* complete valve length for BMB/067b (A) and BMB/071 (B) by excavation unit; line indicates statistically significant difference at the 0.05 level.

Table 3
Relative abundance estimates (MNI and NISP), NISP: MNI fragmentation ratio and mean complete *A. granosa* valve length by site and excavation unit.

Site	Excavation Unit	MNI	NISP	Fragmentation Ratio (NISP: MNI)	Mean Valve Length
BMB/067	1	38	717	18.87	33.3
	2	86	1379	16.03	32.4
	3	141	1882	13.35	31.2
	4	206	1768	8.58	31.7
	5	111	1072	9.66	31.9
	6	208	825	3.97	32.1
	7	102	1330	13.04	31.9
	8	68	813	11.96	32.0
BMB/071	1	132	4854	36.77	29.4
	3	330	9024	27.35	29.8
	5	825	8281	10.04	31.9
	7	547	4086	7.47	30.6
	9	697	5458	7.83	32.2
	11	143	5188	36.28	33.9

Jerardino and Navarro (2008: p. 1024) that mean size may be distorted in favour of larger or smaller size classes due to processes of differential fragmentation of individuals of a particular size class. While there was no independent measure of fragmentation calculated for the samples included in that study, an approach was clearly advocated as a further stage of investigation whereby samples with potentially differing taphonomic histories should be investigated to determine whether there is a clear connection between these processes and differential size preservation (Jerardino and Navarro 2008: p. 1027). As such, where there is a significant relationship between fragmentation rates and mean shell size, albeit one that is not particularly strong as in BMB/071, or

even where there is no significant relationship as in BMB/067b, if particular size classes have become invisible due to analyses based on complete valves alone then these patterns need to be explored further.

5. Investigating *A. granosa* mean valve size

To investigate the potential effects of taphonomic bias within these assemblages, mean size based on complete valve length measurements are compared against those values reconstructed from fragmented valves where complete valve length could not be taken, but where at least one of the other attributes described above could be obtained. These comparisons are made at two different scales, one for each site in total, and the second comparing individual excavation units within each site. In each case, statistical testing of mean size is restricted to complete and fragmentary samples (as opposed to complete plus fragmented), as comparisons should be based on independent samples (e.g. Jerardino and Navarro, 2008: p. 1026; Sokal and Rohlf, 1969). A visual comparison of complete versus complete plus fragmented mean size is also made here, however, to identify any variation in general trends in valve size. There is a degree of variability within and between the two case study sites in the size and structure of the *A. granosa* assemblages. The data presented in Table 4 details the number of valves per site and excavation unit (left, right and total) as well as the number and percentage of measured valves (complete and fragmented). This is restricted to counts of valves that retain those diagnostic criteria required for siding (e.g. umbo and teeth structures). A total of 1828 *A. granosa* valves were identified from the midden site BMB/067b, consisting of 1022 complete (55.9%), 433
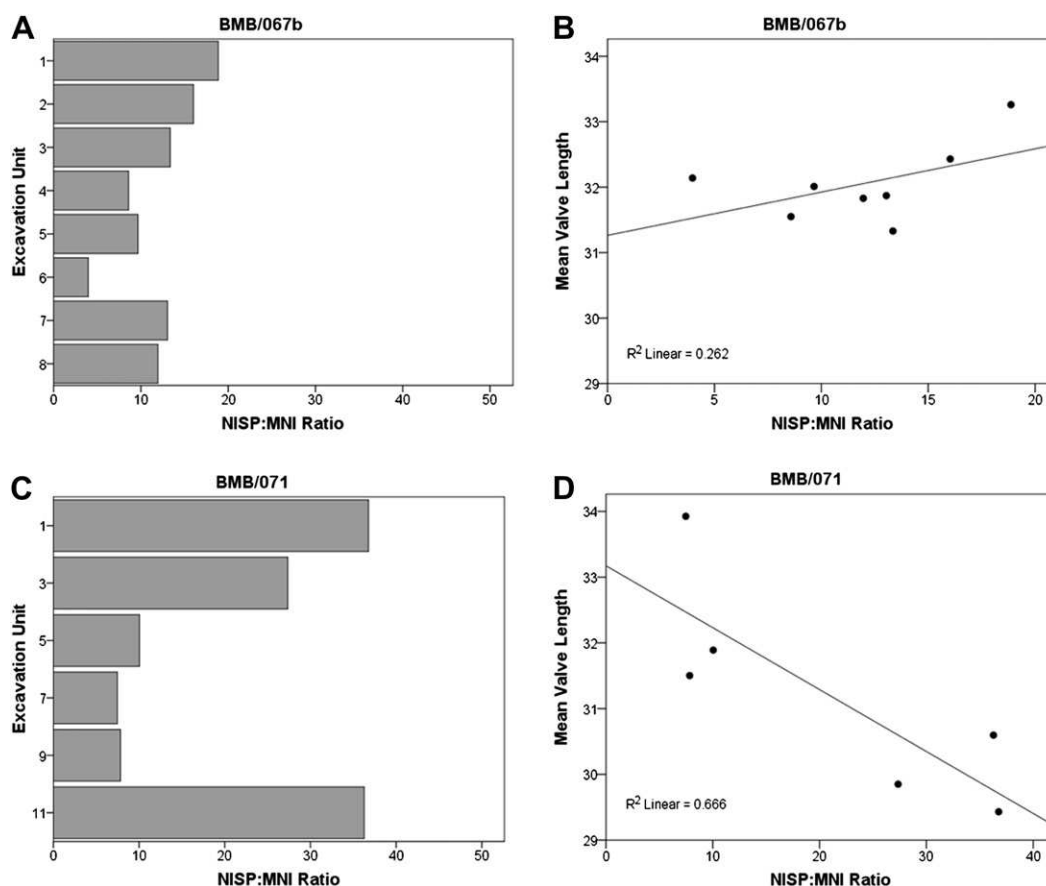

Fig. 6. *A. granosa* fragmentation ratio by excavation unit and scatterplots of mean valve length vs. NISP: MNI fragmentation ratio for BMB/067b (A and B) and BMB/071 (C and D).

Table 4
Number and percentage of measured *A. granosa* valves in the BMB/067b and BMB/071 samples.

Site	Excavation Unit	Left	Right	Total	No./% Complete	No./% Fragments Measured	Total No./% Measured
BMB/067	1	38	34	72	30/41.7%	20/27.8%	50/69.4%
	2	77	86	163	86/52.7%	36/22.1%	122/74.9%
	3	115	141	256	134/52.3%	61/23.8%	195/76.2%
	4	197	206	403	188/46.7%	126/31.3%	314/77.9%
	5	111	106	217	144/66.4%	46/21.2%	190/87.6%
	6	182	208	390	232/59.5%	78/20.0%	310/79.5%
	7	102	98	200	133/66.5%	43/21.5%	176/88.0%
	8	68	59	127	75/59.1%	23/18.1%	98/77.2%
Total		890	938	1828	1022/55.9%	433/23.7%	1455/79.6%
BMB/071	1	132	113	245	138/56.3%	43/17.6%	181/73.9%
	3	330	307	637	325/51.0%	117/18.4%	442/69.4%
	5	825	825	1650	1129/68.4%	279/16.9%	1408/85.3%
	7	547	547	1094	874/79.9%	78/7.1%	952/87.0%
	9	604	697	1301	878/67.5%	195/15.0%	1073/82.5%
	11	128	143	271	181/66.8%	63/23.2%	244/90.0%
Total		2566	2632	5198	3525/67.8%	775/14.9%	4300/82.7%

fragmented valves (23.7%), and 373 valve fragments from which no measurements could be obtained (20.4%). The percentage of complete valves per excavation unit ranges from 41.7 to 66.5%, and in terms of measurable valves when including fragmented shell, this increases to between 69.4 and 88.0%. From the mound BMB/071 a total of 5198 *A. granosa* valves were identified, consisting of 3525 complete (67.8%), 775 fragmented valves (14.9%), and 898 valve fragments from which no measurements could be obtained (17.3%). The percentage of complete valves per excavation unit ranges from 51.0 to 79.9.5%, and for measurable valves this increases to between 69.4 and 90.0%.

Fig. 7A and B presents boxplots for BMB/067b and BMB/071 as site totals. For BMB/067b a *t* test indicates that the mean size of complete *A. granosa* valves (31.9 mm) is not significantly different ($t = -1.12$, df = 634.1, $p = 0.240$) from the fragmented samples (32.3 mm). The overall mean combining the complete and fragmented valves for BMB/067b is 32.0 mm. A similar result has been obtained for BMB/071, where complete mean valve size (31.9 mm) is not significantly different ($t = -0.53$, df = 1240.9, $p = 0.595$) from the fragmented samples (31.8 mm), with a mean of 31.9 mm for the combined complete and fragmented valves. This result differs from those recently presented by Jerardino and Navarro (2008: p. 1027), where there were significant size differences between complete and fragmented limpets recovered from archaeological deposits as fragmentation had affected the integrity of larger shells to a greater degree. As noted by Jerardino and Navarro (2008: p. 1027) in their discussion of the potential effects of taphonomic processes on shell size, one explanation for this dissimilarity relates to processes of differential preservation, shell morphology (including differences

in bivalve and gastropod shell architecture and shell strength) and shell mineralogy. For example, it has been noted that *Anadara* valves feature strong radial ribs and are strongly arched from the dorsal to the ventral margin, shell features that may enhance crushing strength. In contrast, the shape of limpets, being rounded or oval with a pronounced apex, may lend itself to more pronounced marginal damage and fragmentation (Zuschin et al., 2003: p. 54; Zuschin and Stanton, 2001: p. 167). *A. granosa* can therefore be characterised as a relatively robust species that may effectively resist higher levels of fragmentation for even larger valves (Faulkner, 2009: p. 828; see also Muckle, 1985; Zuschin et al., 2003: pp. 54, 69; Zuschin and Stanton, 2001). That said, comparing at a finer scale of analysis the complete and fragmented *A. granosa* by excavation unit within each site draws out a greater degree of variability than is observable at the overall site level.

Boxplots for complete and fragmented valve size by excavation unit are presented in Fig. 8A (BMB/067b) and 8B (BMB/071), with descriptive statistics and *t* test results comparing mean size of complete and fragmented valves by excavation unit detailed in Table 5. For BMB/067b there is no statistically significant difference between excavation units bar unit three, where the mean size of complete valves is significantly smaller than the fragmented sample. In contrast, three of the six excavation units analysed from BMB/071 do show significantly different complete and fragmented mean valve sizes. For units three and seven the mean size of complete valves is significantly smaller than the fragmented sample, whereas the reverse occurs in unit 11. As expected, the mean sizes of the combined sample fall between the complete and fragmented values (Jerardino and Navarro, 2008: p. 1026). These
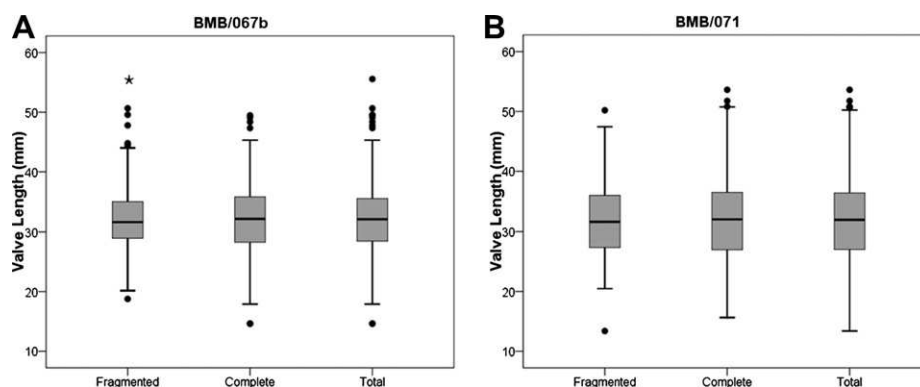

Fig. 7. Boxplots of total *A. granosa* valve length for BMB/067b (A) and BMB/071 (B) relative to the origin of the sample (fragmented, complete and total).
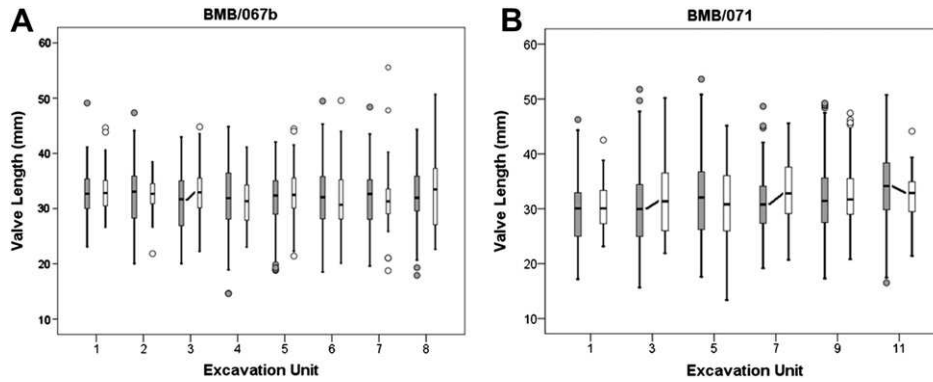
Fig. 8. Boxplots of *A. granosa* complete and fragmented valve length by excavation unit for BMB/067b (A) and BMB/071 (B) (grey = complete valves; white = fragmented valves); line indicates statistically significant difference at the 0.05 level.

are interesting patterns, particularly when referring to the fragmentation data presented above in Fig. 5. These data reinforce the suggestion made above that there is no simple relationship between fragmentation rates, valve size and the potential differential preservation of smaller size classes. Within these sites the larger valves rather than the smaller sizes are preserving to a greater degree, the opposite pattern to that presented for the South African sites, but still one of the potential outcomes outlined by Jerardino and Navarro (2008: p. 1027). The exception here is unit 11 from BMB/071, and this may indicate differences in the taphonomic context for this sample. Given that there is not a significant difference between complete and fragmented mean valve size for these sites in total, the degree of variability between excavation units detailed here raises the question as to whether there are real differences between mean size of complete valves only versus combined complete and fragmented throughout each site.

The comparison of *A. granosa* complete and combined total of complete and fragmented valve size by excavation unit for both sites is presented in Fig. 9. As noted above it is not possible to test the statistical difference between the complete and combined samples, however a comparison of the general trends is still informative. Comparing the complete and combined valve samples from BMB/067b (Fig. 9A and B) indicates that while there are some minor differences apparent, particularly in the distribution of extreme values, the overall pattern does not dramatically change within and between excavation units. As with the analysis of complete valves presented earlier there is no significant change in *A. granosa* size throughout the deposit (ANOVA $F = 0.931$, df $= 1370$, $p = 0.481$). A similar pattern is observable in comparing the

complete and combined samples for shell mound BMB/071 (Fig. 9C and D), where there is a significant degree of variability in mean valve size throughout this deposit for the combined valve sample (ANOVA $F = 27.996$, df $= 4294$, $p = 0.000$). Post-hoc comparisons using the Tukey HSD test were again conducted, and as with the complete valve sample these tests indicate that mean valve size between excavation units three and five, and excavation units nine and 11, are significantly different at 0.05 level. Again, there are some minor differences in the ranges and distribution of extreme values, particularly in excavation units three, five and nine, but the same general trends are apparent in the combined sample as in the original analysis. These results suggest that, even though there are significant differences between complete and fragmented valve sizes within and between deposits, the effects do not appear to be particularly strong. Overall these assemblages are not heavily fragmented, and as noted above relatively small numbers of fragmented valves contribute to the combined samples. As a result, general trends in mean valve size are not dramatically altered when comparing the whole and combined valve datasets.

6. Discussion and conclusion

Recent work has demonstrated the utility of morphometric techniques enhancing or complementing analyses based exclusively on the measurement of complete valves or shells. It was also noted that morphometric equations should be generated for a range of different species around the world, as well as being applied to both new research project and the re-evaluation of existing datasets (Jerardino and Navarro, 2008: p. 1027). The morphometric equations

Table 5
Descriptive statistics and *t*-test results for fragmented and complete *A. granosa* valves by site and excavation unit.

Site	Excavation Unit	Fragmented		Complete		*t* test results	Total	
		μ	σ	μ	σ		μ	σ
BMB/067b	1	34.0	5.4	33.3	5.4	$t = 0.48$, df $= 31.7$, $p = 0.634$	33.5	5.3
	2	32.5	3.7	32.4	5.6	$t = 0.11$, df $= 61.1$, $p = 0.911$	32.4	5.2
	3	33.4	4.8	31.2	5.6	$t = 2.63$, df $= 83.0$, $p = 0.010^*$	31.7	5.5
	4	31.5	4.3	31.7	6.2	$t = -0.33$, df $= 255.4$, $p = 0.743$	31.7	5.5
	5	32.7	5.0	31.9	5.2	$t = 0.76$, df $= 62.8$, $p = 0.452$	32.1	5.1
	6	31.7	5.2	32.1	5.7	$t = -0.54$, df $= 97.7$, $p = 0.592$	32.0	5.6
	7	32.2	6.8	31.9	5.8	$t = 0.19$, df $= 53.4$, $p = 0.853$	32.0	6.0
	8	33.2	7.2	32.0	5.4	$t = 0.65$, df $= 21.5$, $p = 0.525$	32.2	5.7
BMB/071	1	30.5	4.5	29.4	5.9	$t = -1.23$, df $= 89.9$, $p = 0.224$	29.7	5.6
	3	31.9	6.2	29.8	6.2	$t = -2.99$, df $= 203.8$, $p = 0.003^*$	30.4	6.3
	5	31.3	6.2	31.9	6.6	$t = 1.38$, df $= 446.9$, $p = 0.169$	31.8	6.5
	7	33.2	5.7	30.6	5.6	$t = -3.33$, df $= 142.5$, $p = 0.001^*$	31.4	5.7
	9	32.2	5.3	32.2	5.4	$t = -1.67$, df $= 318.6$, $p = 0.095$	31.6	6.0
	11	32.0	4.6	33.9	6.5	$t = 3.07$, df $= 81.0$, $p = 0.003^*$	33.8	6.4

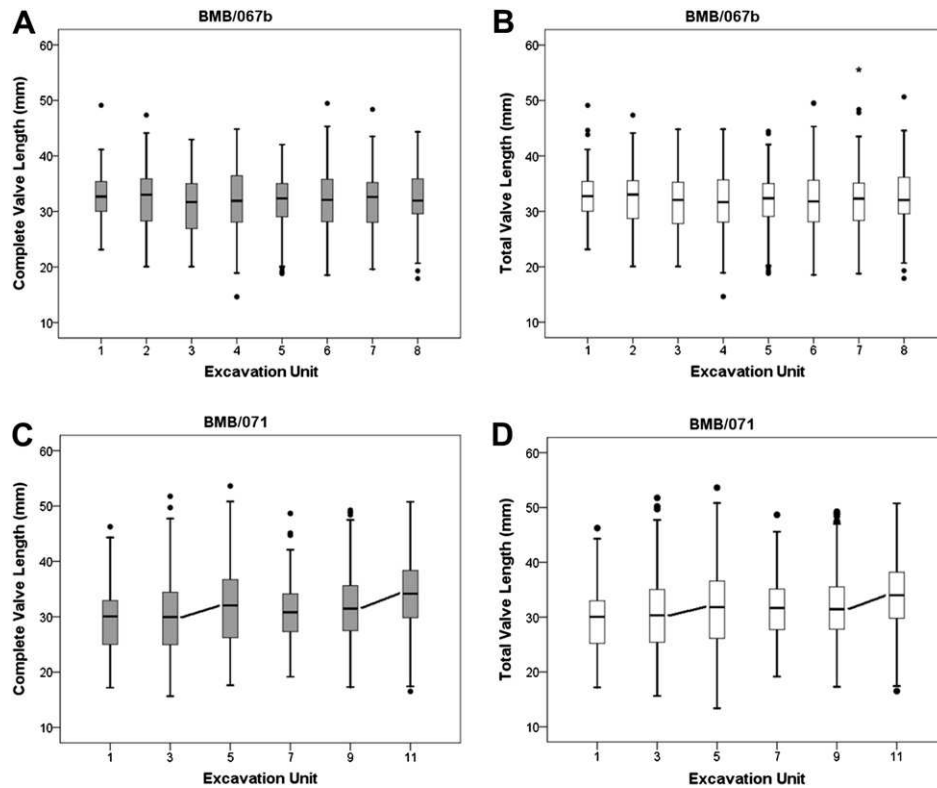* indicates statistically significant difference between fragmented and complete samples.

Fig. 9. Boxplots of *A. granosa* valve length by excavation unit for BMB/067b complete (A) and total combined (B) valves, and BMB/071 complete (C) and total combined valves (D); line indicates statistically significant difference at the 0.05 level.

and the results presented here also indicate that the full range of valve part measurements developed are useful in the reconstruction of valve size due to their strong predictive values. As such, these measurements will also be useful for investigating long-term trends in *A. granosa* size/age structure through time (e.g. Peacock and Mistak, 2008; Randklev et al., 2009: p. 210). There are a number of other benefits to applying these biometric approaches, particularly in highly fragmented assemblages. For example, sample size can be increased to include fragmented as well as complete shells, thereby increasing the statistical validity of the sample obtained from these kinds of shell deposits (Jerardino and Navarro, 2008: pp. 1026–1027; Peacock and Mistak, 2008; Randklev et al., 2009: p. 212). Sample size is not as crucial an issue for the *A. granosa* dominated midden and mound sites in the study area, with large numbers of complete valves in both of the case study sites, and an increase of only approximately 25% with the inclusion of the fragmented valves. That said, the level of fragmentation will still need to be assessed on a site-specific basis, and these methods will be particularly beneficial in highly fragmented deposits.

More importantly in this context, bias in preservation and the extent that taphonomic processes have acted upon a site can also be investigated through an analysis of fragmented molluscan remains. By investigating fragmentation and valve size at a number of different scales (e.g. site and excavation unit), the analysis presented here serves as an extension of the research undertaken by Jerardino and Navarro (2008: pp. 1026–1027), where it was noted that different combinations of taphonomic factors (such as accumulation rates, trampling, etc.) will introduce a degree of differential preservation and produce different trends. To a certain degree, given the difference in morphology and depositional history, this is what we see in the analysis of the Blue Mud Bay case study sites. Related to this is the fact that the relationship between fragmentation and mean valve size within these deposits is not

simple or linear in nature. Reinforcing the original conclusions of Jerardino and Navarro (2008: p. 1027), this means that we cannot expect to see a decrease or increase in mean shell size as fragmentation increases, but rather this must be determined on a site-specific and excavation unit-specific basis, as well as based on the particular molluscan species under investigation (e.g. differential robusticity). Regardless of these aspects and the degree of variability observed within and between the case study sites, the trends observed prior to the inclusion of the fragmented valves do not change significantly. This effectively means that while a certain degree of skewness is evident within these sites, due to low fragmentation levels this does not have a significant effect as the observable trends remain unchanged. While extrapolation across all sites within the study area is not possible based on the analysis of two sites, these results do suggest that a combination of low fragmentation rates, large sample sizes and general *A. granosa* valve robusticity effectively decrease the effects of size bias through fragmentation. As a result, previous interpretations of intensive mollusc exploitation related to the occurrence of shell mounds (Faulkner, 2006, 2009) are still supported here.

The high degree of correlation between valve length and valve height, hinge length, umbo length and umbo height, prove the usefulness of the morphometric equations presented here as a set of analytical tools for investigating prehistoric molluscan populations. Given the general paucity of such studies in Australia in particular, the successful application of the methods outlined here has the potential to increase our understanding of both taphonomic processes and prehistoric molluscan exploitation.

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